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The Total Electron Content of the Ionosphere at Middle Latitudes near the Peak of the Solar Cycle

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16954

Abstract. The electron content of the ionosphere during the period September 1958 to December 1959 has been calculated from observations of the Faraday rotation of the signals from Sputnik 3 recorded at Boulder and Stanford. Diurnal and seasonal effects are pronounced, and from these measurements we deduce daytime temperatures of 1500°K in winter and nearly 2000°K in summer, with a diurnal variation of at least 330°K and very likely as much as 500°K. During magnetic storms, a reduction in total electron content and an increase in scale height are found to accompany the usual decrease in maximum electron density.

Introduction

The radio transmissions from earth satellites have permitted the recording of useful ionospheric data for extended periods in the last few years. The recorded information usually consists of either (1) the received amplitude versus time, from which the polarization rotation can be obtained easily, or (2) the change in Doppler shift imposed by the ionosphere as a function of time. Records of the first type have been discussed by *Garriott* [1960], *Little and Lawrence* [1960], *Yeh and Swenson* [1961], *Blackband* [1960], *Hame and Stuart* [1960], and *Munro* [1962]. Observations of the second type have been described in some detail by *Aitchison and Weekes* [1959], *Ross* [1960], and *de Mendonça* [1962]. Either type of record can be used to estimate the total number of electrons in the ionosphere, or it may be desirable sometimes to combine both types of information, as *de Mendonça and Garriott* [1962] did. The first satellite to provide the opportunity for extended observation was 1958δ_2 (Sputnik 3), which transmitted for almost two years after its launch on May 5, 1958. Storage batteries permitted transmissions from within the earth's shadow during the first year. Although the intermittent character of the radio signals hindered Doppler studies, Faraday rotation measurements were readily accomplished.

In this paper we present the analysis of sixteen months of data, from September 1958 through December 1959, recorded at both the Boulder Laboratories of the National Bureau of Standards and at Stanford University. For over six hundred individual passages of Sputnik 3, near either Boulder or Stanford, the value of the electron content of the ionosphere was computed. From these calculations the diurnal and seasonal variations of content have been obtained. Since the penetration frequency of the ionosphere was measured at each receiving location near the time of the satellite passage, a scale height for the ionization distribution above the level of F-region peak density could also be estimated. The seasonal and diurnal variation of this scale height (H) is also shown. Finally, the effect of magnetic storms on electron content and scale height is investigated.

The observational data consist of amplitude versus time records of the signals from Sputnik 3. Most records were obtained at a frequency of 20 Mc/s, but some of the Stanford data were obtained at 40 Mc/s. The receivers being connected to dipole antennas resulted in a fluctuating signal strength (of the order of one fade per second) because of the rotation of polarization of the arriving radio waves. This 'Faraday rotation' is, of course, due to the birefringent property of the ionosphere. Each of the two nearly circular characteristic modes follows an independent path from satellite to receiver. As the phase path lengths of these modes vary with

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time at a slightly different rate, the two waves 'beat' together, resulting in a rotation of polarization. Each half-rotation produces one fade on the amplitude versus time record. In the next section the method in which these records are used to obtain the electron content of the ionosphere will be described.

Analysis

As long as the wave normals never become perpendicular to the magnetic field within the ionosphere, the total number of full polarization rotations at any time is equal to one-half the difference in the number of wavelengths along the two ray paths. This is expressed as

$$\Omega = (P_o - P_x)/2\lambda_0 \quad \text{full rotations} \qquad (1)$$

where the ordinary and extraordinary phase path lengths are in units of length, and λ_0 is the free space wavelength. The rotation angle is nearly directly proportional to the integrated electron density, as can be seen by the approximate expression for Ω that is used by most authors:

$$\Omega \approx \frac{K}{2\pi f^2}\left(\frac{B}{\mu_0}\right) \cos\theta \sec\chi \int_0^{h_s} N\, dh \qquad (2)$$

where K is a constant equal to 2.97×10^{-2} in mks units, f is the wave frequency, (B/μ_0) is the magnetic field intensity (amp/meter),[1] θ is the angle between the wave normal and the magnetic field vector, χ is the angle between the ray and the vertical, N is the electron density, and the integral extends up to the height h_s of the satellite. The geometrical factor, $(B/\mu_0)\cos\theta \sec\chi$, varies slowly along the ray path and properly belongs inside the integral, but it is frequently removed by the process of taking its average value, suitably weighted, over that part of the ray path that lies in the ionosphere. If, for the moment, we assume the satellite to be in a circular orbit and the ionosphere to be spherically stratified, we see that the rotation angle changes with time only because of changes in the geometrical factor, $(B/\mu_0)\cos\theta\sec\chi$. (It is also assumed that the electron density is unchanging during the brief period of a satellite passage.) Although we cannot directly measure the rotation angle, it is quite simple to count the number of fades between two times and then divide by 2 to get the change in Ω during this time interval. This observational quantity can be related to the integrated electron density by

$$\Omega_1 - \Omega_2 \equiv \Delta\Omega = (K/2\pi\mu_0 f^2)(B_1\cos\theta_1\sec\chi_1 - B_2\cos\theta_2\sec\chi_2)\int_0^{h_s} N\, dh \qquad (3)$$

where the subscripts refer to the two times of observation.

One of the simplest ways to obtain the integrated electron density is to estimate the geometrical factor at each of the two times with the aid of magnetic field calculations similar to those of *Yeh and Gonzalez* [1960]. With $\Delta\Omega$ obtained from the recordings, the integrated density is readily calculated from (3). The approach used in this paper is intended to provide a more accurate estimate of the geometrical factors above.

The procedure used here involves the calculation of the ordinary and extraordinary phase-path lengths by the digital ray-tracing technique described by *Lawrence and Posakony* [1961]. Two times were first selected, one when the satellite was to the north of the observing station, and the second when the satellite was near the closest approach to the observing station. From the recorded satellite signals, the number of fades, equal to twice the change in Ω, was determined. From the satellite ephemeris, the position of the satellite at each of these times was computed. Then an accurate ray tracing was made between the observer and satellite positions for these two times and for each of the two modes. A spherically symmetric model ionosphere was used having a critical frequency equal to that recorded at the appropriate time by an ionosonde in the vicinity of each station. The profile of the model ionosphere corresponded to the real-height profile obtained from an analysis of the ionogram up to the height of maximum density. Above the height of maximum density, a Chapman layer ($N = N_{max}\exp\frac{1}{2}[1 - z - e^{-z}]$, where $z = (h - h_{max})/H$, and H is the scale height of the ionizable constituent) was assumed with $H =$ 100 km. On some satellite passages, it was necessary to estimate the critical frequency when satisfactory ionograms were not available. On

[1] The symbol (B/μ_0) is used for magnetic field intensity in order to reserve the symbol H for scale height.

these occasions, the Chapman profile was used at all heights.

From the four phase-path lengths that were computed, the estimated change in rotation angle is obtained as

$$\Delta\Omega' = [(P_{o_1} - P_{x_1}) - (P_{o_2} - P_{x_2})]/2\lambda_0 \quad (4)$$

This estimate will, of course, differ to some extent from the observed value, $\Delta\Omega$. It is then assumed that the difference between the computed and estimated change in the rotation angle is due entirely to an inaccurate estimate of the integrated electron density in the model ionosphere. This is a very good approximation (for a spherically stratified ionosphere), as can be seen from (3), in which $\Delta\Omega$ is proportional to the integrated electron density. Although the geometrical factor is to some extent affected by refraction in the ionosphere, most of this small error has been removed by ray tracing through a model very similar to the actual ionosphere. With this assumption, the integrated density of the model is increased or decreased in the proportion necessary to make $\Delta\Omega' = \Delta\Omega$.

Since the height of the satellite will change slowly from day to day as the perigee moves in latitude, the integrated electron density will change even if the identical electron distribution should exist on all occasions. To eliminate the dependence of the calculations on satellite height, *the electron content of the ionosphere has been defined as the total content of electrons in the model ionosphere required to make* $\Delta\Omega'$ $= \Delta\Omega$. The content of electrons in the model is obtained by integrating the Chapman profile to infinity. However, only satellite passages above 600 km have been used in this analysis, which implies that the difference between the total electron content and the electron density integrated to the height of the satellite is never more than about twenty per cent. Usually it was less than ten per cent.

One source of error in the procedure outlined above results from the rotation of the transmitting antenna in the satellite relative to the receiving antenna. If rotation with respect to the receiving dipole should occur, extra fades not associated with the Faraday rotation might be observed (see *Thomson* [1958] for a more detailed analysis). It appears from the records that the spin rate of the satellite usually had a period of almost a minute, which was much slower than the Faraday fading rate and thereby could not introduce serious error. However, at night, when the Faraday fading rate was quite slow, the satellite spin may have altered the results to a noticeable extent.

The most important source of error, however, was almost certainly the use of a spherically symmetric model ionosphere in the ray-tracing program. To minimize this error, one pair of rays was traced when the satellite was to the north, as close as possible to the region of propagation transverse to the magnetic field. When propagation approaches the transverse condition, $\cos\theta \to 0$, and the rotation angle in (2) tends toward zero. The other two rays were traced to a point as near the observer's zenith as possible. In this ideal situation, transverse propagation at one point to the north and the satellite overhead at the other point, horizontal gradients do not affect the computed results. This follows from the fact that $\Omega_2 = 0$ at the point of transverse propagation, and $\Omega_1 = \Delta\Omega$ overhead. In practice, it is not possible at the latitudes of Boulder and Stanford to make $\Omega_2 = 0$. However, (Ω_2/Ω_1) averaged about 0.4 and at least reduced the error due to horizontal gradients. It is difficult to state the accuracy with which the electron content has been determined, but it is believed that the results are accurate to within twenty per cent in almost all cases, and probably to within ten or fifteen per cent in most instances.

Results of the Analysis

Seasonal and diurnal variation of total content. Figure 1 shows the total electron content of the ionosphere as deduced from more than 600 satellite passages from September 1958 through December 1959. In each passage the satellite was at a height greater than 600 km, and the planetary geomagnetic activity index, K_p, was less than 5. The measurements from periods of high magnetic activity are discussed separately. The values are plotted as a function of local mean time (lower scale), and the approximate date of each observation appears at the top. The LMT assigned to each data point was obtained at the intersection of the ray path between the observer and the satellite with a spherical shell 300 km above the earth's surface. Inspection of the data revealed no systematic differences between the results of northbound

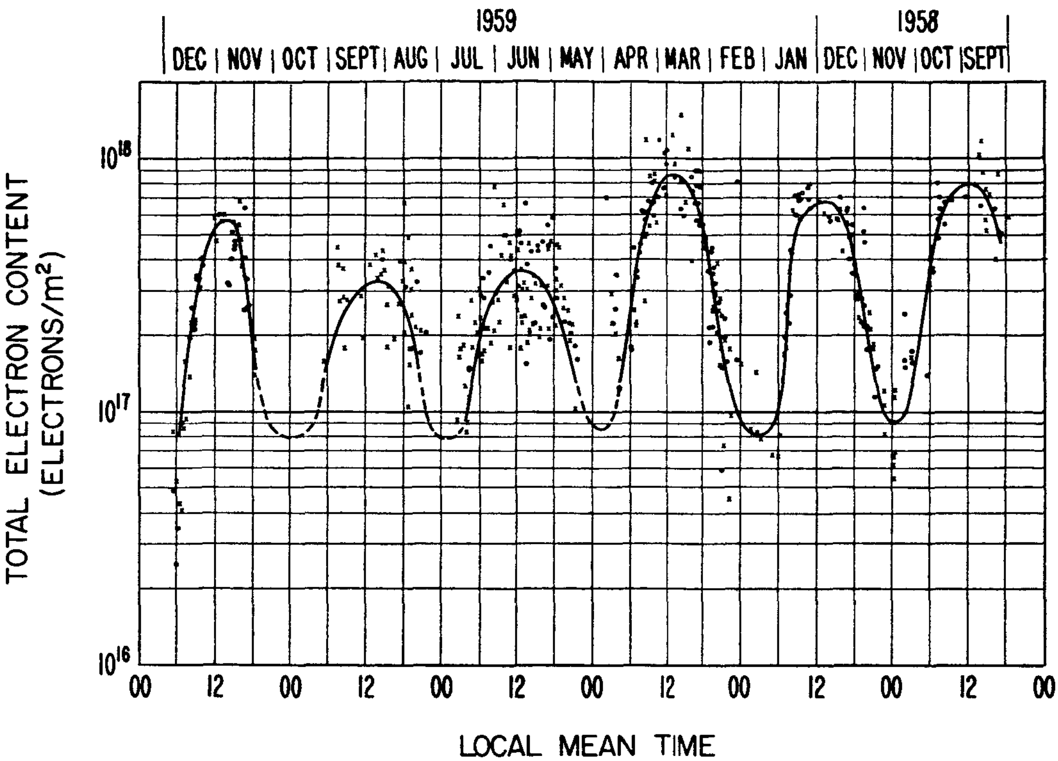

Fig. 1. The total electron content of the ionosphere as deduced from Faraday rotation observations of 1958δ_2. The circles represent observations at Stanford; the crosses are those at Boulder. Local time increases toward the right, going through six cycles in order to separate observations made in different seasons.

and southbound satellite passages; thus no distinction has been made between them. Likewise, the passages observed at Stanford and at Boulder show no appreciable systematic differences, but a different symbol is used for each station in the figure. The smoothed curve has been drawn by hand through the points to indicate the approximate diurnal and seasonal variation of the mean total electron content.

The most striking characteristic of Figure 1 is the pronounced diurnal variation which, during the winter months and during the spring of 1959, reached a magnitude of 10 to 1. During the summer and fall of 1959, the magnitude of the diurnal variation decreased markedly, accompanied by a rather large decrease in the maximum value of total content that occurs in the early afternoon. Thus it is the daytime values of total content that show a winter maximum, the nighttime values being more nearly independent of season. This seasonal effect follows the variation of f_oF_2 during the same period and shows a tendency to lag behind the phase of the sun's declination. During the year December 1958 to December 1959, the smoothed monthly mean sunspot number dropped from about 180 to about 130, and the ionospheric electron content shows some tendency to follow this reduction.

Before proceeding further, it would be useful to compare the present results with those obtained in earlier analyses. *Garriott* [1960] showed the diurnal variation of electron content in an eight-month period calculated from part of the same original data used in this paper. Two methods of calculation were used, one depending on the rate of Faraday fading and the second similar to that used in this paper, except that a less accurate ray-tracing scheme was employed. *Yeh and Swenson* [1961] also used the Faraday fading rate of the Sputnik 3 signals to calculate the electron content. These earlier results, together with the smoothed curve of Figure 1, are shown in Figure 2. We see that the curve of agree well with the assumed scale height of 100 km.

Figure 3 shows the average values and standard deviations of the scale height of the equivalent Chapman region for twelve-hour periods centered on local noon and midnight. As in Figure 1, times of magnetic disturbance have been eliminated, and the observations from different months have been kept separate. The values of scale height average around 100 km, in good agreement with the value used for the model ionospheres in the ray-tracing process. There is, however, a marked difference between the scale heights at summer and winter solstices. This seasonal variation of scale height from 90 to 120 km corresponds to a temperature variation from about 1500°K to 2000°K if the plasma is composed of atomic oxygen ions in thermal equilibrium with the electrons.

These values of scale height and temperature can be compared with those deduced by other workers using various techniques. Satellite-drag data provide independent measurements of temperature, and *Kallmann-Bijl* [1961] has estimated the daytime temperature to be about 1800°K in 1958–1959. (Her scale height of the total pressure is, however, smaller than the scale height of the ionizable constituent derived in this paper.) Frequently electron density profiles have been obtained from rocket flights and incoherent-scatter sounders. *Bowhill* [1962] has normalized a number of these data to remove

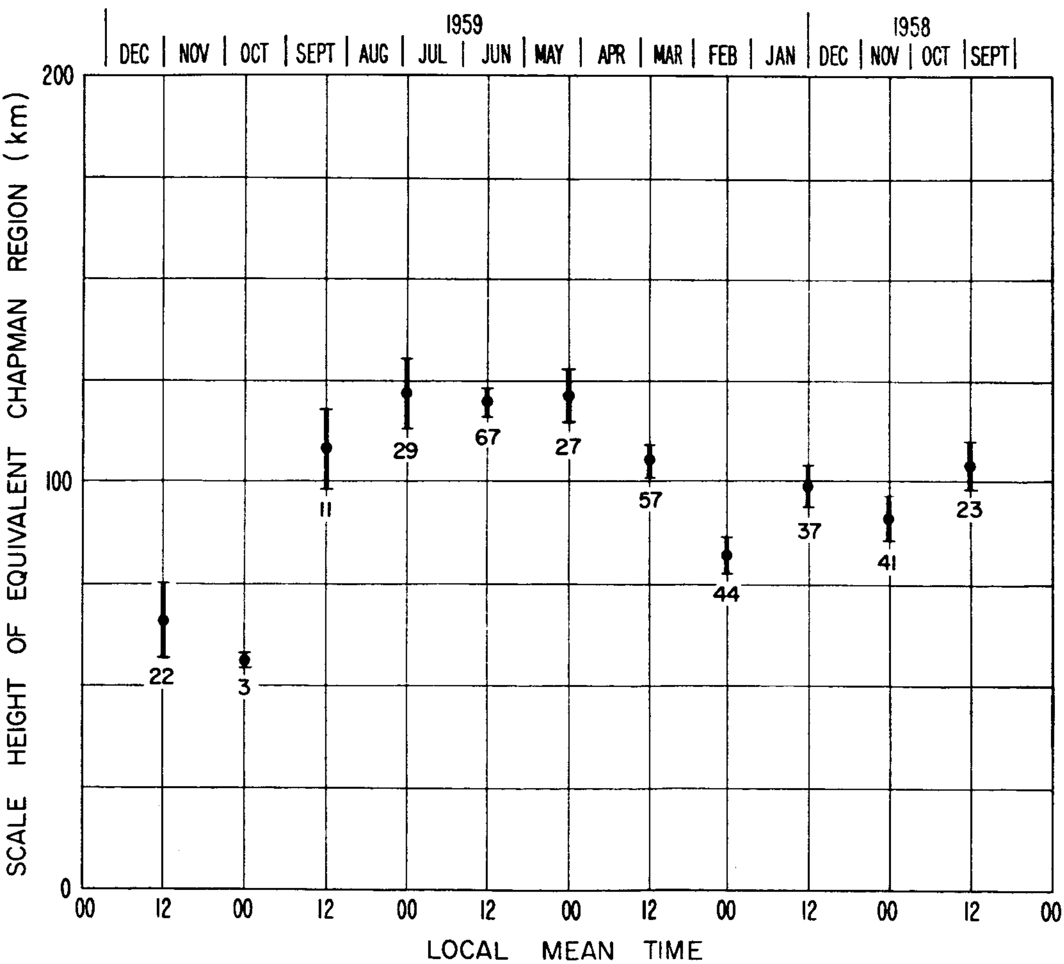

Fig. 3. The seasonal variation of the twelve-hour average values of the scale height of the equivalent Chapman region. The bars indicate the standard deviation of the mean, above and below the mean value; the numbers below them indicate the number of observations.

the effect of variations in the amount of atmospheric heating. The temperatures were corrected to the constant value of 10-cm solar flux density of 200 × 10^{-22} watt $m^{-2}(c/s)^{-1}$. Usually these temperatures were in the range of 1600°K to 2000°K in the daytime. The moon echo measurements of total electron content made by *Evans and Taylor* [1961] in January and February 1960 imply daytime temperatures of only about 1000°K. Unfortunately, it was not possible to extend the Sputnik 3 data in this paper the few additional months necessary for a direct comparison because passages became too low near the demise of the satellite. However, the December 1959 results in Figure 3 are much lower than those in December 1958 and are reasonably close to the estimates based on moon echoes. Thus, much of the evidence, including the results of this paper, points to a daytime temperature of 1500°K to 2000°K during the times of high solar activity.

To look for a diurnal variation of scale height, we have had to remove the pronounced seasonal effect. To do this we calculated the difference between each original value of scale height and the value predicted for that season of the year by a smooth curve drawn through the points in Figure 3. The resulting residuals were averaged by one-hour groups as shown in Figure 4. They display a marginally significant diurnal variation with a minimum in the evening and a maximum during the early morning hours. The scale height is about 20 km greater at noon than in the early evening, presumably indicative of a temperature variation of about 330°K.

There are several reasons for believing that the actual diurnal temperature variation is somewhat greater than that implied by Figure 4. First, we have used a scale height of 100 km in the model ionosphere for ray-tracing purposes on all satellite passages. Figure 4 suggests that 110 km by day and 90 km in the evening might have been more realistic selections. We have previously noted that the value of the model scale height does affect the calculated value to some extent, and a correction can be estimated on the basis of results of the test case mentioned above. The test case implies that the actual variation of scale height was more nearly 115 to 85 km between daytime and evening hours. This would amplify the diurnal temperature variation to nearly 500°K. Second, the shape of the equilibrium electron density profile may not be the same for daytime and nighttime. The normalized equilibrium profiles obtained by *Bowhill* [1962] contain about 4 per cent fewer electrons by day than by night. If these profiles were accepted, the diurnal temperature variation would be further amplified by about 60°K.

The variation of scale height with h_{max}. The values of scale height are plotted versus the height of maximum electron density in each 25-km interval of h_{max} in Figure 5. Clearly H tends to increase with h_{max}. Although it may be thought that this provides evidence for a scale height gradient in the ionosphere, it appears

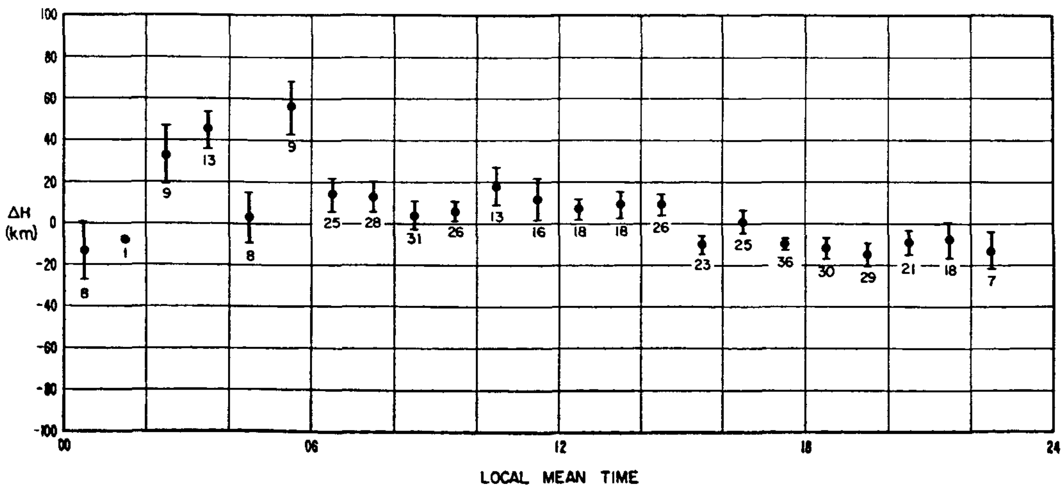

Fig. 4. Diurnal variation of the difference between observed scale heights and a smooth curve through the average values given in Figure 3.

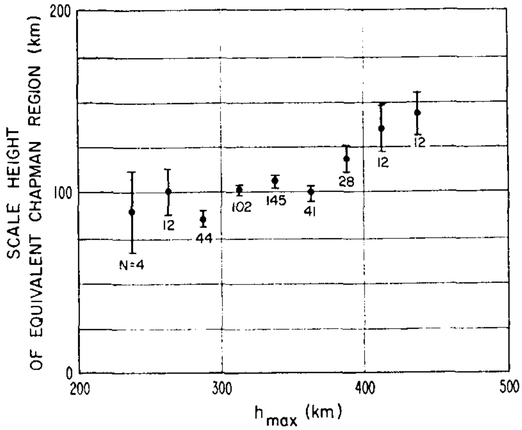

Fig. 5. The variation of scale height of the equivalent Chapman region as a function of the observed height of maximum electron density. The bars indicate the standard deviation of the mean above and below the mean value; the numbers below them indicate the number of observations.

more likely that the results are another manifestation of atmospheric heating. If we assume that the maximum electron density always occurs near the same pressure level in the atmosphere, increased heating will raise the height of all constant pressure levels as well as increasing H. With this interpretation, Figure 5 shows the relation between the increase in scale height or temperature and the expansion of the atmosphere at the pressure level of maximum electron density.

The effect of geomagnetic storms. It is well known that at temperate latitudes one of the prominent ionospheric effects of a geomagnetic storm is a decrease in the maximum electron density. The behavior of total electron content is less well substantiated, although several workers [*Hame and Stuart*, 1960; *Taylor*, 1961] have reported a corresponding decrease. We have compared our values of total electron content during magnetic storms with the quiet-day curve in Figure 1 and simultaneously compared the maximum electron density (N_{max}) with its normal quiet-day value. Figure 6 shows the result for all cases in which $K_p > 5$. Decreases in N_{max} are much more common than increases, and they tend to be accompanied by decreases in total electron content. To see more clearly whether the quantities N_{max} and total electron content vary in proportion, thus keeping the scale height the same, we have plotted in Figure 7 the average value of scale height as a function of K_p. There is a definite indication that the scale height above the F peak does rise during a magnetic storm, this implying that the total electron content usually does not decrease so much as does the maximum electron density of the layer.

Conclusion

The electron content of the ionosphere has been calculated from observations of the Faraday fading of the signals from Sputnik 3. The data were taken in a 16-month interval between September 1958 and December 1959 at the National Bureau of Standards, Boulder, Colorado, and at Stanford University, Stanford, California. The diurnal variation is clearly evident, since the orbital precession permits all local times to be observed approximately every three months.

These measurements can also be related to another of the important physical parameters of the ionosphere, that is, the temperature. A convenient way to do this is by assuming the shape of the electron density profile, which provides the proportionality constant between electron content and scale height or temperature. We have assumed a Chapman profile that is nearly the shape deduced from the theoretical analysis of *Bowhill* [1962]. A daytime temperature of

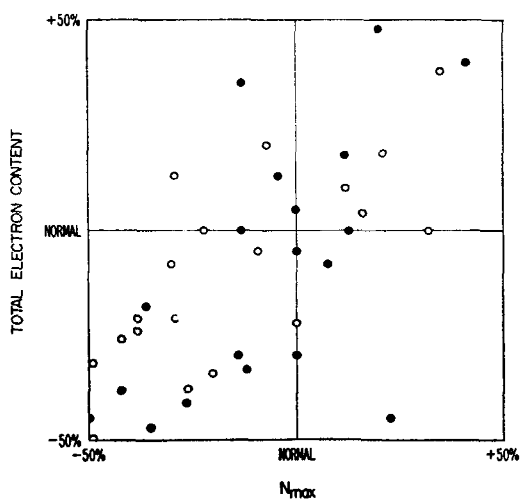

Fig. 6. Observations made during geomagnetic storms indicating the variation from the quiet-day mean values of total electron content and of maximum electron density. Open circles are Stanford data; closed circles are Boulder data.

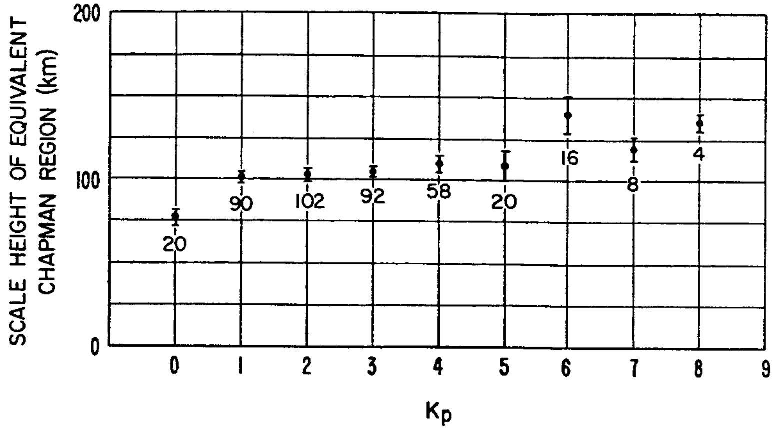

Fig. 7. The variation of the scale height of the equivalent Chapman region as a function of the planetary geomagnetic activity index K. The bars indicate the standard deviation of the mean above and below the mean value; the numbers below them indicate the number of observations.

1500°K to 2000°K is obtained in this way. The diurnal variation of temperature obtained, at least 330°K and very likely as much as 500°K, is comparable with that previously found from satellite drag analyses. The seasonal variation is quite pronounced, varying from about 1500°K in the winter to about 2000°K in the summer in 1958–1959. A long-term variation, presumably the solar-cycle dependence, can also be seen, but it seems too early for definitive comparisons with sunspot number or solar radio flux. When three or four years of continuous data have accumulated, it should be possible to make more useful estimates of the solar-cycle dependence. Recent work by several authors [e.g. *Evans*, 1962] has suggested that thermal equilibrium between the ions and the electrons does not exist in the daytime. When this is true, the temperatures we have deduced in this paper should be considered the mean of the ion and electron temperatures.

The effect of magnetic storms on the ionosphere is found not only to reduce the electron content when the maximum electron density is depressed, but also to increase the scale height of the ionization. Further evidence for the effects of atmospheric heating is found in the increase of H with h_{max} on magnetically quiet days.

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